REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(LEAVE BLANK)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	19 July 1999	Professional Paper

4. TITLE AND SUBTITLE

Turning Down Wind? Don't Lose the Axis!

5. FUNDING NUMBERS

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Naval Air Systems Command
47123 Buse Road, Unit IPT
Patuxent River, Maryland 20670-1547

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Discussions have continued in the aviation press over the past 24 years between pilots as to whether or not there is a thing called the "Downwind Turn Phenomenon." Opponents to the theory (principally airline pilots) say, "If you fly Needle, Ball, and Airspeed, you will never get yourself in trouble!" They are, of course, right - IF the aircraft is flown in this manner. Proponents say that no, "When I fly my crop-duster to a visual ground reference it IS different turning downwind than when turning into the wind!" Every article of the opponents elicits about six letters to the editor from crop-duster pilots restating their position and beliefs. The logic of their arguments has not convinced a single one of the airline pilots. Truth of the matter, though, is that the crop-duster pilots are also RIGHT. This is an emotionally charged issue for the pilots on both sides (e.g., How dare you tell me how I fly my aircraft!!!). In the meantime, we continue to wreck aircraft, which is why I continue to try and explain this problem.

14. SUBJECT TERMS

Cycloid Trochoid U-control Wind Axis Earth Axis

15. NUMBER OF PAGES

17

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

CLEARED FOR
OPEN PUBLICATION
19 Jul 99
PUBLIC AFFAIRS OFFICE
NAVAL AIR SYSTEMS COMMAND
H. Howard

TURNING DOWN WIND? DON'T LOSE THE AXIS!!

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ABSTRACT

Discussions have continued in the aviation press over the past 24 years between pilots as to whether or not there is a thing called the "Downwind Turn Phenomenon". Opponents to the theory (principally airline pilots) say, "If you fly Needle, Ball, and Airspeed, you will never get yourself in trouble!" They are, of course, right - IF the aircraft is flown in this manner. Proponents say that no, "When I fly my crop-duster to a visual ground reference it IS different turning downwind than when turning into the wind!" Every article of the opponents elicits about six letters to the editor from crop-duster pilots restating their position and beliefs. The logic of their arguments has not convinced a single one of the airline pilots. Truth of the matter, though, is that the crop-duster pilots are also RIGHT. This is an emotionally charged issue for the pilots on both sides (e.g., How dare you tell me how I fly my aircraft!!!). In the meantime, we continue to wreck aircraft, which is why I continue to try and explain this problem.

The arguments proposed on both sides are flawed. They fail to maintain continuity of reference to the chosen axis system (Earth or Wind) and, further, fail to show the relationship of one to the other. This relationship is key to understanding how the wind affects a flight vehicle. The best article that I have read on the subject is one that was written by Oleska-Myron Bilaniuk and published in the October 1986 Soaring magazine, reference (a). I agree with almost everything that he says, including that the ground track of turning aircraft flown in the wind axis is a cycloid. I don't agree with his parting comment that "It's too hard." It isn't all that complicated and, further, the theories that apply to the U-control modeler flying in the wind, "feathering" helicopter rotor blades in forward flight, and an aircraft making a steady level turn in a steady wind are all consistent. It takes POWER, however, to transfer axes.

This paper will:

a. Reiterate the position that I stated during my presentation at the 1991 Society of Flight Test Engineers (SFTE) national conference (Session IV, Flight Test Methods, "Analysis Tools Derived from Investigating LTE", reference (b)), which was as follows: "I can determine winds aloft and true airspeed of the aircraft using ONLY a time history of the ground track of a level 360 deg turn."

b. Provide the data and proof that I have done so.

c. Provide the test methodology. This method can be a basis for Airspeed Calibration using Radar, Cinethodolite, or Differential Global Positioning System.

d. Provide analysis of three wind-related accidents, including that of the Cessna Cardinal 177B on 11 April 1996 at Cheyenne, Wyoming.

e. Finally, provide a set of charts, which will relate wind speed to aircraft speed and define the ground track in terms of the turn diameter.

ACRONYMS, ABBREVIATIONS, SYMBOLS, DEFINITIONS, AND NOTATION

This complex area requires some amplification to the existing definitions for clarity. My definitions are included below:

Cycloid - Geom. Special case of the family of curves known as Trochoids (see definition below). A curve traced by a point at the radius (on the circumference) of a circle which rolls without slipping through one complete revolution along a straight (or curved line) in a single plane such as a stone in the tread of a tire; Common Cycloid; Trochoid.

Trochoid - Geom. A family of curves defined by tracing a point on the radius, or extension of the radius of a circle which rolls without slipping through one complete revolution along a straight (or curved) line in a single plane. If the point is at the radius or on the circumference of the circle (stone in a tire tread), it is called a Cycloid or Common Cycloid (see definition above). If the point is less than the radius of the circle (e.g., lug nut or valve cap location), the curve is called a Curtate Cycloid and appears like a stretched sine wave. If the point is outside of the radius of the circle (e.g., outermost point on the flange of a railroad wheel), it is called a Prolate Cycloid and looks like overlapped circles with "loops". As the point on the radius becomes very large in relation to the radius of the circle (prolate cycloid), the curve approximates a circle. As the point radius gets very small in relation to the circle (e.g., at the axle), the curve approximates a straight line.

Downwind Turn Phenomenon - The "Downwind Turn Phenomenon" is a turn into or out of the wind in which the pilot deliberately or inadvertently transfers from flying in the wind axis (Needle-Ball-Airspeed) to flying fully or partially constrained to a visual ground reference. In this turn, improper or inadequate compensation is made for the effects of the wind. Turning into the wind is characterized by increasing airspeeds and/or climbing flight and turning downwind by decreasing airspeeds and/or descending flight. If the margin to stall is insufficient in the downwind turn, the aircraft may STALL. (This is exactly what rotor blades do in high-speed forward flight, known as Retreating Blade Stall.)

INTRODUCTION

My interest and involvement in this topic goes all the way back to high school days. I noticed that my U-control model tended to climb while turning into the wind and descend while turning out of the wind unless I applied a little down elevator upwind and a little up elevator turning downwind. The worst case that I ever saw of this climbing-descending problem was at a model meet at Connelsville, Pennsylvania, in the mid 50's where a beautiful P-38 U-control model started climbing into the wind and descending turning downwind. It continued climbing and descending, uncorrected, until the wind rolled the model in on the cables and it crashed. My interest in airplane modeling led me into Aeronautical Engineering where I took both flight training and a flight testing course in college. One of the bad habits that I had as a flight student was getting low and slow in the pattern, especially turning downwind. It didn't make me very comfortable and to make matters worse the flight instructor couldn't give this Aerospace Engineering student a very satisfactory answer as to why that would happen. He just kept saying, "Watch your airspeed, watch your airspeed, watch your airspeed". I was to learn later, after I started flight testing helicopters, that rotor blades climb and descend just like the U-control model in the wind unless they are "feathered", decreasing angle of attack going into the wind and increasing angle of attack going out of the wind. The U-control model is physically constrained through the two cables to the hand of the pilot to fly around him in a circle at a constant radius in the ground axis system. Consider the pilot the "axle". Rotor blades are physically constrained to fly around the rotor hub and shaft position and "articulated" blades move up and down (flap), forward and backward (lead lag), and change pitch angle (feather) as they go around the shaft in a circle. The climbing and descending motion of the U-control model and that of the rotor blades result from the same aerodynamic forces. Both are due to the change in wind velocity upwind and downwind for the former, and rotor blades going into and away from the constant airspeed of the helicopter in the latter. In this case, the main rotor shaft is the axle.

Helicopter level forward flight performance in flight testing is defined and normalized by a nondimensional parameter μ, defined as the ratio of the forward speed of the helicopter divided by the rotor blade tip tangential speed. μ is analogous to J in propeller theory except that it is the in-plane component of velocity instead of the propeller shaft axial velocity.

I first read about the "Downwind Turn Phenomenon" in an article in the March 1975 issue of Air Progress (reference (c)). In that article, there were two pilots who, at that time, were flying for the same airline and argued the pros and cons of the subject. That was shortly after completing the U.S. Navy Test Pilot School as an academic student in class 39. What followed several months later in the Radio Control (R/C) model press were more articles also about turning downwind, climbing and descending flight, and stalling the aircraft. These articles were just as ambiguous and also brought no satisfactory conclusions. It took me about 4 months of pondering this problem to arrive at what I think is a "solution" or "explanation", and my first effort was a proposed article to the R/C model press, rejected by Radio Control Modeler and American Aircraft Modeler as being "too controversial".

Over the years, I have followed articles by airline pilots Schiff (references (d) and (e)), Garrison (reference (f)), and Horne (reference (g)). In the issue after each article, the crop-dusters respond (reference (h)), as do the R/C modelers. Nobody to date has made a convincing argument with the exception of Oleska (reference (a)). I believe everything that he says in his article with the exception of that "it's too hard". It is NOT.

In 1991, I presented a paper at the SFTE conference relative to the Unanticipated Right Yaw, reference (b). During the presentation, I projected that I could, using only the ground track time history, calculate the winds aloft, true airspeed, and bank angle of an aircraft doing a level turn maneuver in the air mass. On 10 April 1992, I gave a data card to LT Scott Weller and he flew two level turns at altitude. The Cycloid mathematics approach was presented in the prior paper, reference (b), and is repeated in this paper for completeness in appendix A. An airspeed calibration method based on the cycloid math approach is presented in appendix B.

ACCIDENTS ANALYZED

BRITISH NORTH SEA OIL RIG ACCIDENT

I read an article in the September 1993 Issue of Rotor and Wing (reference (i)) about a Super Puma which crashed just after takeoff while turning downwind in a 50 kt wind. I became interested in the analysis because of the inconsistency in described rate of descent (6 ft/sec) with the stated altitudes at 20 and 10 sec to impact (250 and 100 ft, respectively). My thought was that the average rate of descent for this 10 sec period would be 15 ft/sec and sufficient to have entered Vortex Ring State at least 10 sec prior to impact. I plotted the limited data in the article and then constructed assumed time histories for altitude, airspeed, and bank angle and calculated and plotted 3 sec increments of turn rate, turn radius, ground track angle, positions North and East of the Oil Rig. The airspeed and rate of descent plot that I came up with put the Puma in Vortex Ring State at 180 ft and 13 sec prior to impact (according to Walkovitch, reference (j), figure 10), and the position plot had the aircraft impacting the water at 2,025 ft on the 066 deg radial from the takeoff Oil Rig. This analysis was briefed at the Navy Helicopter Association conference in April 1995. The very next presenter was Mr. Ron Stewart of Stewart-Hughes whose company made the flight data recorder on the accident aircraft. I was provided a copy and therefore able to subsequently base an analysis on the flight data recorder information. Results of this analysis showed that the aircraft entered Vortex Ring State at 13 sec to impact at 233 ft and impacted the water at 1,875 ft on the 068 deg radial. Appendix C, figure 1, is a copy of my initial data plot constructed from the reference (i) data with annotated impact point information from the flight data recorder. Appendix C, figure 2, is the ground track information based on the flight data recorder, showing the takeoff and intended landing Oil Rig. Appendix C, figure 3, contains the ground track flight profiles for initial, flight data recorder, and cycloid method approaches. What it shows is that the cycloid method very well represents the initial ground track of the flight data recorder. Appendix C, figure 4, is the cycloid-based plot of 50 kt wind and 68 kt airspeed of where the Super Puma SHOULD HAVE GONE if it were flown Needle-Ball-Airspeed in a level turn in the air mass instead of switching to visual ground reference, which is what reference (i) says that he did. In fact, appendix C, figure 2, has "upper" and "lower" arrows along the ground track. The "upper" arrows represent the aircraft heading, while the "lower" arrows represent the pilot's look-around angle of 135 deg relative to aircraft heading. This is pertinent because the pilot went past a point where he could see the Oil Rig, slowed down, and fell into Vortex Ring State. The pilot in the reference (k) incident recovered his aircraft, but he was at a higher altitude.

CESSNA CARDINAL 177B, N35207

Much has been written about the Jessica accident. References (l), (m), and (n) all apply covering the gamut from parenting to flight training to the laws on who is a pilot to human factors and fatigue. The NTSB covered the accident in their "Blue Cover" report, reference (o).

I have provided an analysis to Mr. Steven McReary of the NTSB having to do with the ground track of the accident aircraft, something not recorded in the aircraft or on the ground. The "Blue Cover" report on this accident (reference (o)) to my mind misses several key points, which are:

1. The aircraft was flyable, as it got to 400 ft.
2. The crosswind would have been pushing the aircraft sideways on a ground track

relative to heading of over 45 deg.

3. There was a water tower on the map in the probable flight path, which may have distracted the flight instructor flying in the right seat (to visual – looking for the tower).
4. The airspeed indicator was on the left panel in front of Jessica.

What this means is that the flight instructor would have been looking to his right at about 45 deg or so out the side window, but having to look to the left about 45 deg to monitor his AIRSPEED. That requires turning his head about 90 deg between where he was going on the ground track and the absolutely necessary critical flight instrument on the instrument panel, especially in the "illusion of speed" environment. I don't know if the FI was a "groundie" or an "airie" (reference (a)), but I don't believe he was using a 90 deg head-turn instrument scan. There are many similarities between this and the Oil Rig accident described prior. The "downwind turn phenomenon" in large measure caused these crashes, in my opinion.

Reference (o) lists the following for Cessna 177B, N35207:

GW of 2,596 lb
Density altitude of 6,670 ft
Airspeed 81 KCAS (MPH)
True airspeed 77.4 KTAS at 243 magnetic
Wind 23 gusting to 32 (assumed steady at 25)
Takeoff heading 300 deg
Wind relative to flight path = 300 – 243 = 57 deg left of the nose

I have calculated the wind speed ratio of 25/77.4 as 0.323 and reference to the final charts can determine the ground track that should have been flown. I have also calculated the Kinetic Energy (KE) in both the wind axis and earth axis for a 25 kt wind condition and scaled the vector size to 400,000 ft-lb/in. (to tip of the arrow) for both "wind" and "earth" axes and presented them in appendix C, figure 5. I did this to emphasize the magnitude of the differences, which are based on velocity squared. They are color-coded blue for the wind axis (reference = the balloon), and this is what the "airies" (Schiff, Garrison, etc.) are talking about (e.g., it doesn't matter turning upwind or downwind - it is the same). The earth axis KE (groundspeed) vectors are Green (upwind), Yellow (crosswind), and Red (downwind) calculated based on groundspeed.

For M35207 at 81 MPH CAS with 25 kt wind, turning from crosswind (Yellow arrow - KE = 688,906 ft-lb) to upwind or downwind if flown in the air mass (with respect to the RE/MAX balloon) doesn't matter. If the pilot biases his ground track and flies to the ground axis (like the crop-dusters do), it **DOES** matter. Going from crosswind (KE = 688,906 ft-lb) to downwind (Red arrow - KE = 1,205,808 ft-lb) in a ground-based turn requires expending more energy. That is why the aircraft will tend to slow down, the climb angle will be less, and it may STALL. The pilot in a ground-based turn (turn around a point on the ground, etc.) transfers energy twice per turn by varying bank to change the turn radius to compensate for the wind.

Table 1 presents the KE calculations on which appendix C, figure 5, is based. The last column in table 1 shows the change in altitude by trading altitude for AIRSPEED to maintain a KE balance as the aircraft turns to a ground reference. That is **exactly** what rotor blades do in forward flight (unless they are "feathered") and a U-control model does in a wind (unless you give it up elevator going downwind and down elevator going upwind). The theory here is consistent.

Table 1
KE ANALYSIS FOR CESSNA 177B, N35207 ACCIDENT
4/11/96

Gross Weight (lb) = 2,596
Wind (kt) = 25
Vector Standard (ft-lb/in.) = 400,000

Flight Direction	Wind Axis Vw (kt)	Wind Axis KE (ft-lb)	Wind Axis Vector Length (in.)	Earth Axis Vw (kt)	Earth Axis KE (ft-lb)	Earth Axis Vector Length (in.)	Delta KE (ft-lb)	Altitude Change(1)
Crosswind	77.4	688906.1	1.72	77.4	688906	1.72	0	0
Upwind	77.4	688906.1	1.72	52.4	315748	0.79	373158	144
Downwind	77.4	688906.1	1.72	102.4	1205808	3.01	-890060	-343

NOTE: (1) Reflects altitude gain/loss (+/-) in feet for circular ground track flown visually for turning from crosswind to upwind or downwind based on exchanging kinetic for potential energy in a "level" turn.

CH-53 PORT AU PRINCE ACCIDENT

In my opinion, the aircraft in this incident was inadvertently overloaded followed by a power check on spot one of the carrier, where up-flow of about 15 deg of the relative wind over the spot indicated sufficient margin of power to go. The pilot transitioned into forward flight, sliding right and starting a downwind turn. As he completed a 90 deg turn, he started to pick up the wind component from the rear (flying visual at about 25 kt), and the airspeed started to bleed off. As he turned further downwind, the aircraft settled slowly into the water (settling with power) and began spinning (loss of tail rotor effectiveness (LTE)). This was the subject of the prior paper. The pilot was able to jettison the 8,000 lb auxiliary tanks, and recovered the aircraft. Turning downwind in a low speed visual environment trying to maintain "airspeed" contributed in large part to this incident.

OTHER REFERENCES

Ray Prouty, writing about the LTE problem in helicopters in reference (p), warns pilots "Don't be fooled by the speed at which objects on the ground or sea are passing by during a downwind turn". George Thelan in reference (q) about a sailplane stall accident calls the problem "Sensory Overload".

PROPERLY FLOWN FLIGHT PROFILES - CUT AND DRIED

Appendix C, figure 6, is the culmination of all of this work. This figure presents lines of ground track for a properly flown level turn at various wind speed ratios. It defines the ground track lines in both the crosswind and downwind directions in terms of percent of the diameter of the circle flown in the air mass. Turn diameter can be calculated using the equation in appendix B or the chart in the center (appendix C, figure 6A) extracted from reference (r). This one figure covers left turns on the left (appendix C, figures 6B and 6D) and right turns on the right (appendix C, figures 6C and 6E) and upwind turns on the bottom (appendix C, figures 6D and 6E) and downwind turns on the top (appendix C, figures 6B and 6C). The dual X scale on the figure represents both % of diameter crosswind position for the ground track and aircraft heading change (0 to 180 deg) from the start position relative to the wind. If, for example, the pilot is flying a known downwind offset from the centerline of the runway (such as 4,000 ft) at a known airspeed (such as 90 KTAS), he could use the central figure (appendix C, figure 6A) to determine bank angle. This problem would indicate a bank angle of about 20 deg to fly a continuous level turn to the centerline of the runway. If the wind were 36 kt, then wind ratio would be 36/90 or 40%, represented by the triangles on the figures. If it were a left turn from downwind to final, the triangles on appendix C, figure 6D, would apply. The other scale represents the headings of 0, 36, 72, 108, 144, and 180 deg, respectively, that the aircraft would have at the appropriate line. Ground track angle relative to the aircraft is the difference between heading and the tangent to the curve at the selected point. If the pilot turns at the numbers, he would have to add 62% of the diameter (62% of 4,000 ft = 2,480 ft) extra in the downwind direction for the turn upwind or, said differently, the level turn will be completed on centerline 2,480 ft short of the numbers.

AIRSPEED CALIBRATION METHOD

Since the ground track of an aircraft flown in the wind follows the mathematical laws of the trochoid family of curves, it only makes sense that the problem can be worked backward. Given the time history of the ground track, we can calculate the aircraft true airspeed, winds aloft, and the bank angle. The airspeed calibration test method of appendix B does exactly this; covering determination of winds aloft for a properly flown level turn based only on the ground track time history shown in appendix C, figure 6. It's cut and dried.

Fly safe, especially turning downwind.

APPENDIX A
CYCLOID MATHEMATICS DEVELOPMENT

NOTATION FOR FIGURE 1 (repeated from reference (b))

A - Point on the radius that defines aircraft airspeed (shown on extended radius) in the wind axis.

C - Wind axis reference (at canter of circle).

D - Diameter of circle flown by aircraft in the wind axis (= 2A). The diameter of the circle flown in the wind axis is the same as the "diameter" of the trochoid in the crosswind direction.

DD - Diameters downwind = Parametric displacement of the aircraft in the downwind direction for one complete circle flown in the air mass - Ratio to the diameter of the circle flown (= X/2A).

E - Earth axis reference.

H - Aircraft heading = θ + 90 deg.

k - Wind advance ratio = $\dfrac{\text{Wind Speed}}{\text{Aircraft Speed}} = \dfrac{Vw}{Va} = \dfrac{W*w}{A*w} = \dfrac{W}{A}$

L - Location of the aircraft in the earth axis reference system.

P - Progression = downwind position of C, the wind axis (= θ*W) for the case shown.

Pi - π = 3.14159.

θ - Rotational angle of wind circle.

Va - Velocity of aircraft (= A*w) in the wind axis.

Vw - Velocity of the wind at C, the reference point (= W*w).

W - Radius of the circle defining wind speed (wind axis).

w - Rotational velocity of wind circle.

X - Displacement of L, the aircraft position, in the downwind direction (earth axis).

Y - Displacement of L, the aircraft position, in the crosswind direction (earth axis).

THE WIND AXIS, EARTH AXIS, AND GROUND TRACK

A source (reference (a)) indicates that wind effects for steady winds can be characterized by cycloid mathematics. The equations of the cycloid, as shown in figure 1 (reference (b), figure 18) are as follows:

$X = W*\theta - A * \sin\theta$
$Y = W - A*\cos\theta$

If we begin at the earth axis reference point "E" and $\theta = 0$ and increment one turn in the wind to $\theta = 360$ or $2*\pi$, the X equations at the start and ending positions become the following:

for $\theta = 0$	$X = W * 0 - A * 0 = 0$
for $\theta = 360$	$X = W *2 * \pi - A*0 = W * 2 * \pi$

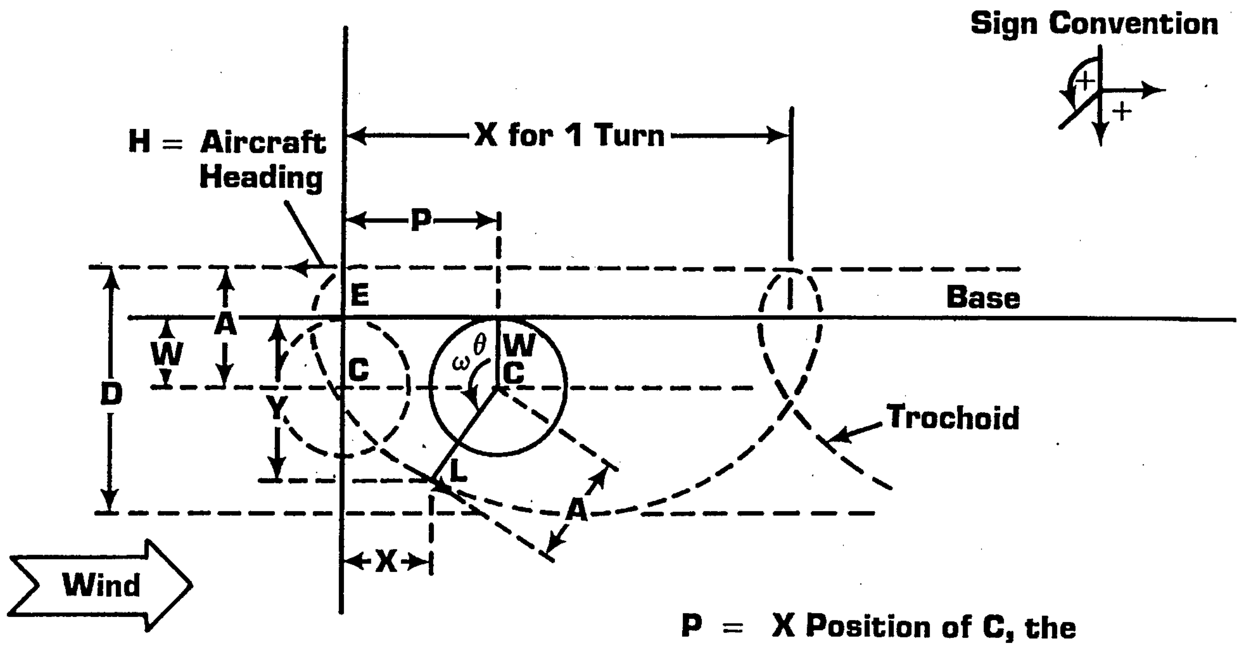
The distance traveled in the X or downwind direction is then the difference between the X dimension at $\theta = 0$ and that at $\theta = 360$. This dimension is $W*2*\pi$. If we then divide both sides of the X equation by the diameter of the circle D (= 2*A) (these diameters are the same in the crosswind direction), the equation becomes the following:

$X/D = X/2*A = W*2*\pi/2*A = W/A*\pi = k*\pi$

If we define the value "k" or "wind advance ratio" as the ratio of wind speed to aircraft speed (k = W/A) and the value X/2A as a "parametric diameter" based on the diameter of the circle flown, we have the following:

Diameters downwind = $k * \pi *$ (diameter)

If we note that the distance traveled in the X dimension or downwind equals k, the ratio of the wind speed to the aircraft speed or "wind advance ratio", times π, we can build some very useful plots which can be used to define the effects of steady winds on a flight vehicle as shown in reference (b), figure 19. We can also note, for rule-of-thumb purposes, that for a 360 deg turn in the wind, the flight vehicle will drift downwind exactly k*pi*(diameter of the turn). The relation between true airspeed, bank angle, and radius of turn can be found in reference (r), figure 2.29. In addition, cycloid mathematics allows us to draw the profiles for various "k" or wind speed to aircraft speed ratios, as shown in reference (b), figure 20. This is a very powerful method for understanding wind effects on a flight vehicle and a pilot can visualize what the ground track of a turn flown in the wind axis system (reference = the axle of the wheel, shown at C on figure 1) should look like based on the "k" ratio. Appendix C, figure 6, takes the family of curves shown in reference (b), figure 20, and starts them at a common point for turning downwind (appendix C, figures 6B and 6C) and concludes them at a common end point turning into the wind (appendix C, figures 6D and 6E). The point is that a pilot without a reliable airspeed indication system and lacking a good "situational awareness" will try to fly groundspeed and get in trouble. The rule-of-thumb ($k*\pi*$(diameters downwind)) for one turn and ground track profiles will help the pilot with his wind solution problem.



$X = W \cdot \theta - A \sin\theta$

$Y = W - A \cos\theta$

L = Location of Aircraft

P = X Position of C, the Wind Reference (C at $X = W\theta$; $Y = W$)

E = Earth Axis Reference (Origin)

C = Wind Axis Reference (Center of Circle)

Figure 1
CYCLOID FLIGHT PATH DEFINITION

APPENDIX B
DETERMINATION OF WINDS ALOFT FROM GROUND TRACK TIME HISTORY

On a zero wind day, a pilot can fly a level turn, maintaining bank angle, turn rate, radius of turn, etc., and - without watching the ground - he will consistently come back to his starting point. In a steady wind, flying the same maneuver will put him back to the starting point, but drifted downwind by a distance equal to the wind speed times time for the turn. In the air mass, however, the pilot is back at the starting point as though it were a zero wind day. Flying the maneuver against a hot-air balloon (which then becomes the reference for the air mass) can prove this. The following procedure is based on the assumption that an aircraft doing a constant rate, constant bank angle, level turn in a steady wind will return to its starting point in the air mass. It also uses the mathematics of the Cycloid.

The test method involves doing a procedure level turn as follows: Roll into a level turn. Once stabilized in the turn, select an up-coming heading and call out "mark" on the heading, on the "mark" start a stopwatch. Continue turning for a complete turn (360 deg) back to the same heading and call "mark" again. On this "mark" stop the stopwatch. In this procedure, you have done a 360 deg level turn in the air mass, arriving back at the starting point (same as a no-wind day). The vector distance on the ground track from first to second "mark" represents the wind vector. Its direction is the wind direction and its distance represents the wind acting on the aircraft over the time period of the turn and, therefore, a simple time * speed = distance problem to calculate the wind speed. From airplane turning performance, the diameter of the circle flown in the wind axis is given by the following equation relating speed and bank angle to the diameter:

$$d = 2r = \frac{2*V^2}{11.26*\text{Tan (Bank Angle)}}$$

These are shown in the enclosed pages from "Aerodynamics for Naval Aviators" of 1960. Another equation defines rate of turn (ROT) in relation to speed, bank angle, and turn rate as follows:

$$ROT = \frac{1{,}091*\text{Tan (Bank Angle)}}{V}$$

The width of the cycloid ground track circle in the crosswind direction is the same as the diameter of the circle in the air mass, therefore, the turn diameter in the air mass can be measured in the crosswind direction on the ground track. These two measurements (wind vector and turn diameter) are made from the ground track for a 360 deg turn. If you use the relationship that distance downwind (DD) due to the wind for a level 360 deg turn equals Wind Advance Ratio (WAR) * PI* Diameter of the turn (DT), you can determine the WAR by the equation WAR = DD/PI*DT. If you have the wind speed calculated from the wind vector, you can calculate the airspeed in the turn using $Vt = Vw/WAR$. If that doesn't work for you, remember that circumference of the circle in the air mass is PI * Diameter, and you have the time for one turn. It is then just a measured circular ground course and a time - distance problem. Using this method, you can tell the pilots what airspeed and bank angle they flew and what the winds aloft were after the fact having only the time history of the ground track (assuming he flew a steady level turn).

This method can be used to:

1. Determine the winds aloft - Insitu.
2. Calibrate airspeed/altitude in turning flight and use in conjunction with mathematics of the cycloid and airspeed and bank angle sensors to:
3. Provide a ground track forecast for a maneuvering aircraft.

WAR - Wind Advance Ratio = Wind Speed (or Vw)/trimmed aircraft flight speed (constant for any wind/airspeed relationship).
Vt - True Airspeed - A time-distance calculation from a ground track gives true airspeed. The aircraft indicated airspeed needs to be converted to calibrated and then using density to true.

APPENDIX C
FIGURES

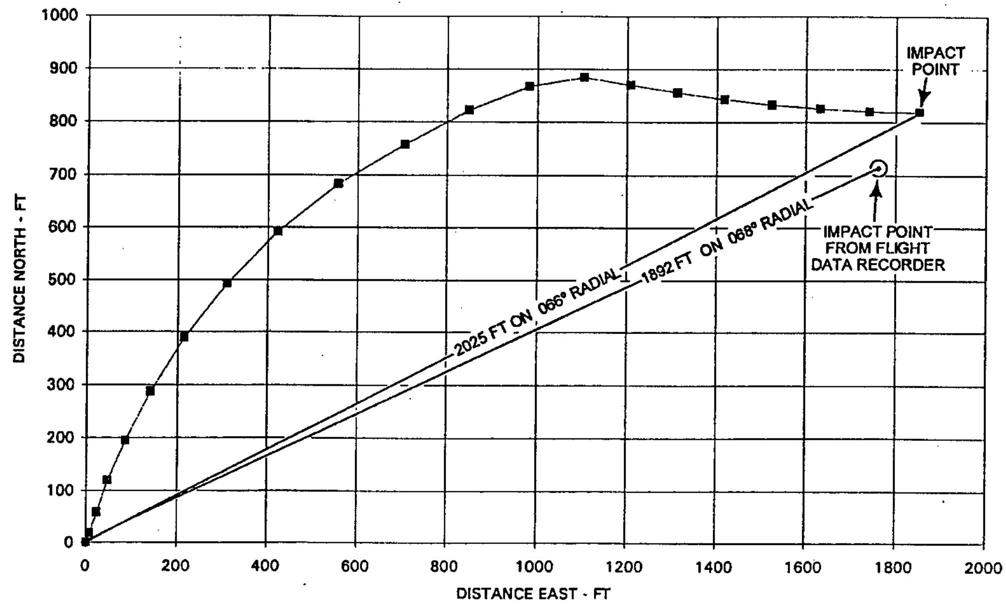


Figure 1
ESTIMATED POSITION
ROTOR AND WING ARTICLE

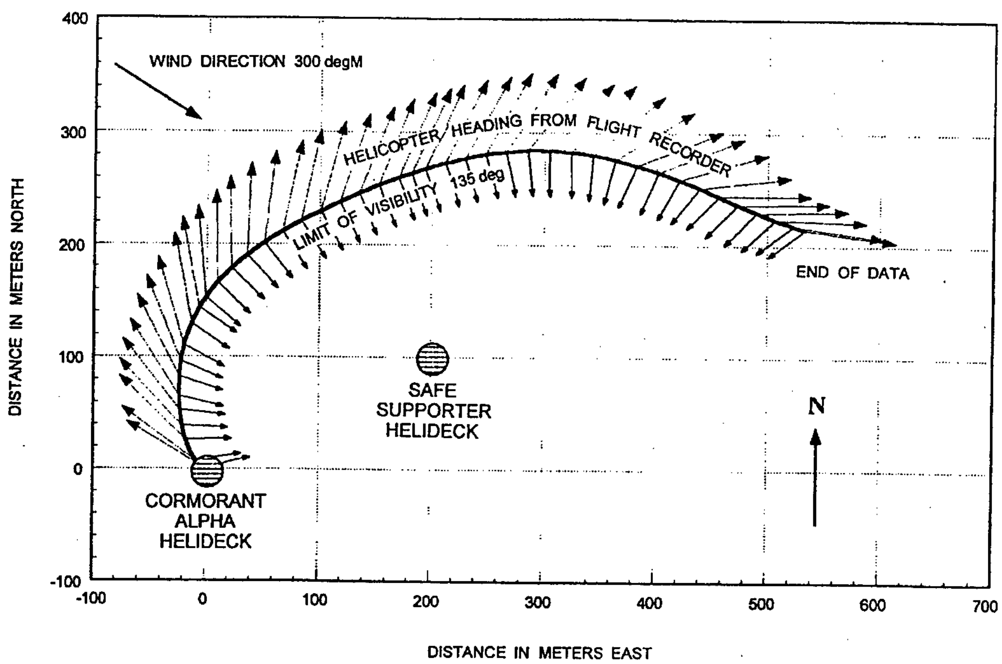


Figure 2
G-TIGH TRACK PLOT SHOWING HEADING AND LIMIT OF VISIBILITY

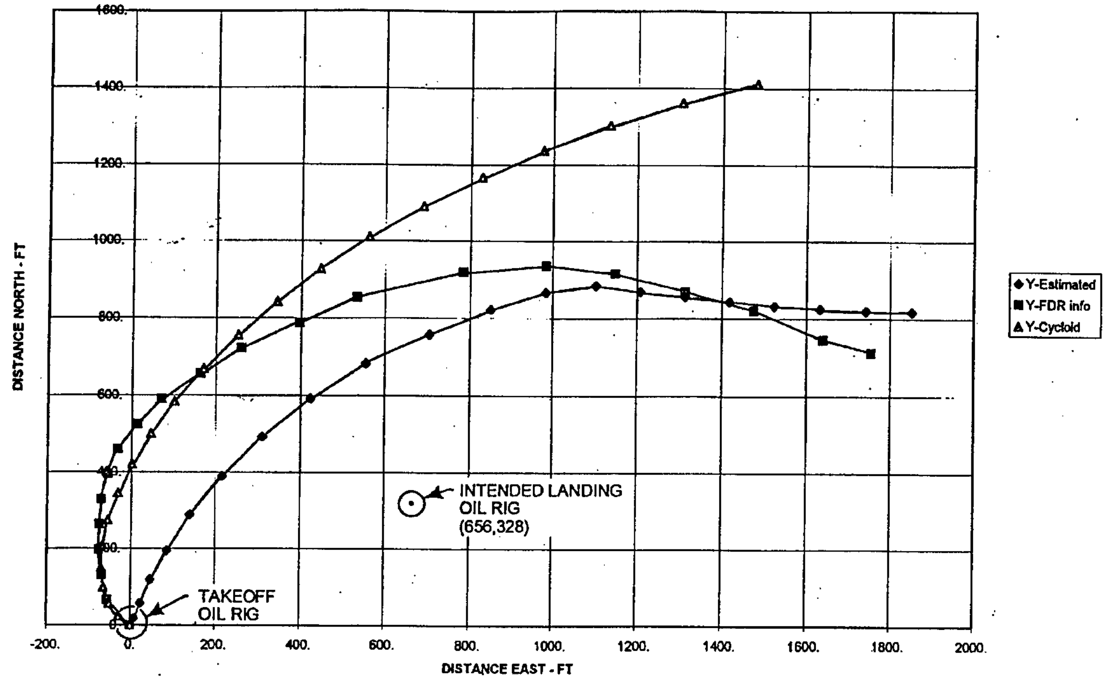


Figure 3
ESTIMATE, FLIGHT DATA RECORDER, AND CYCLOID COMPARISON

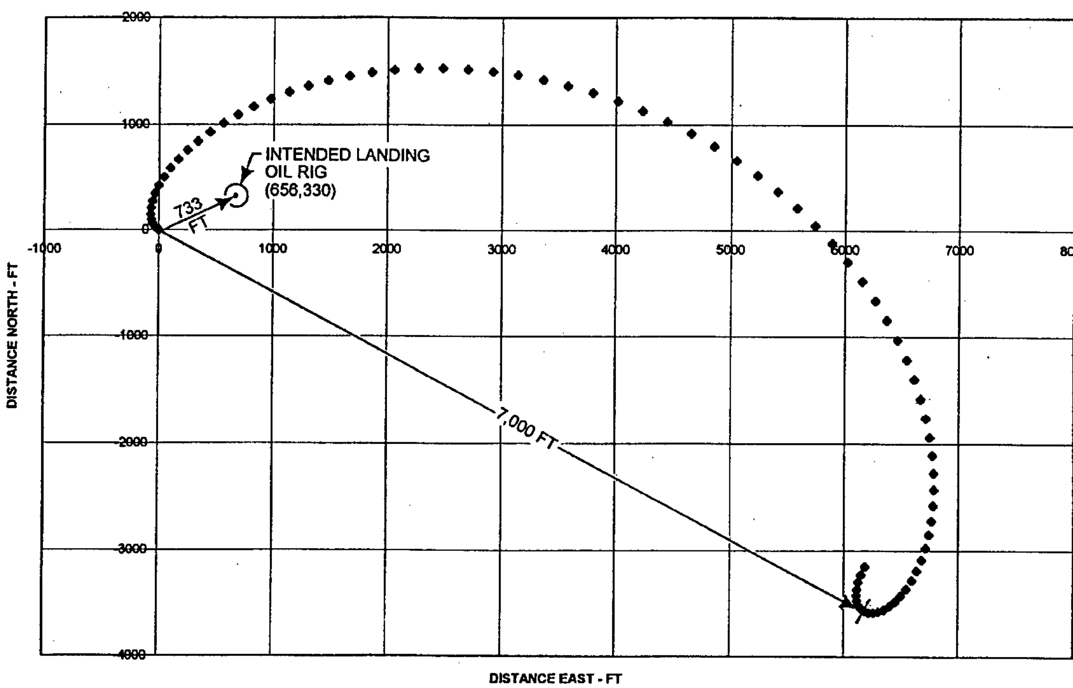
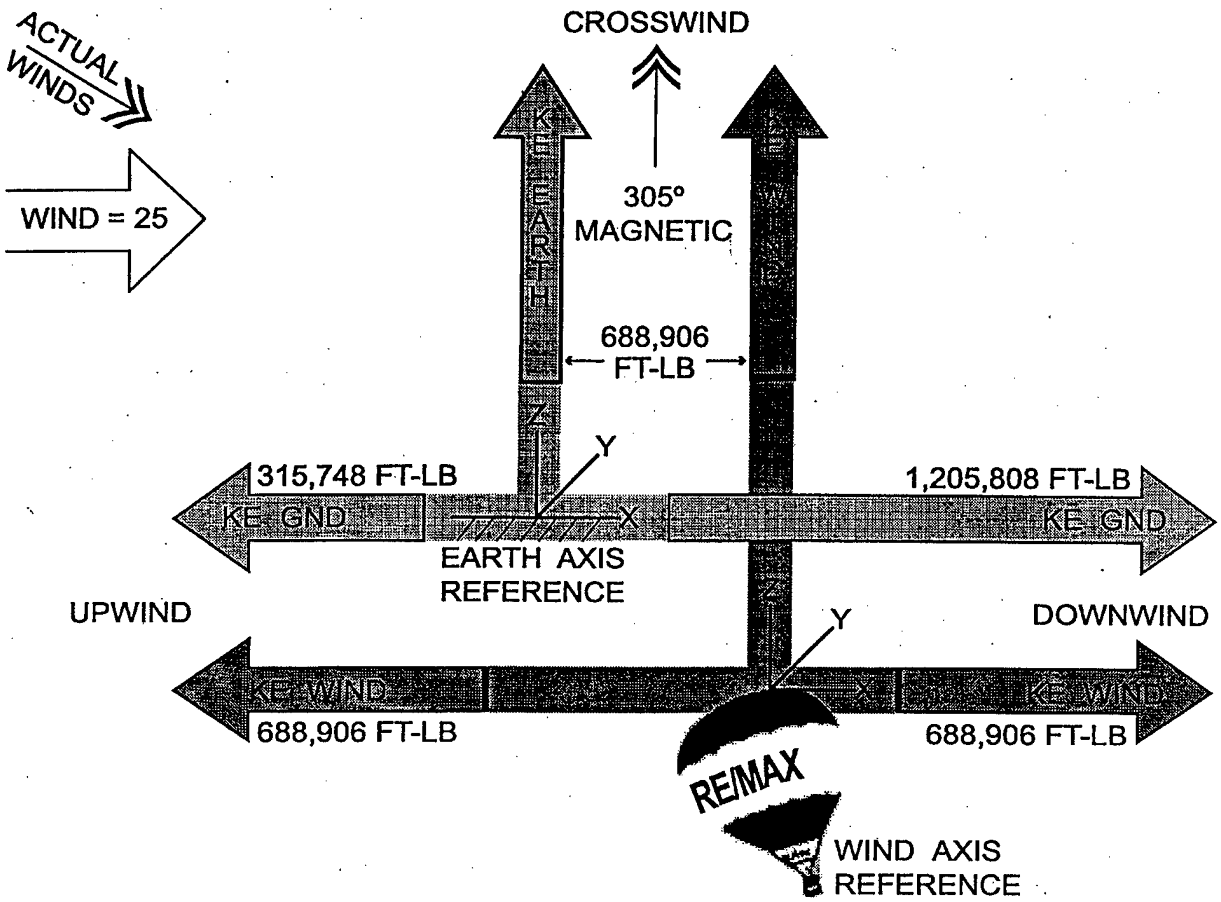


Figure 4
ONE TURN FLIGHT PROFILE
(RELATIVE WIND = 300 DEG)



CESSNA 177B, N35207 ACCIDENT
4/11/96
25 KT WIND 77.4 KTAS
1 IN. = 400,000 FT-LB KE

Figure 5
WIND AND EARTH AXIS
KE VECTORS

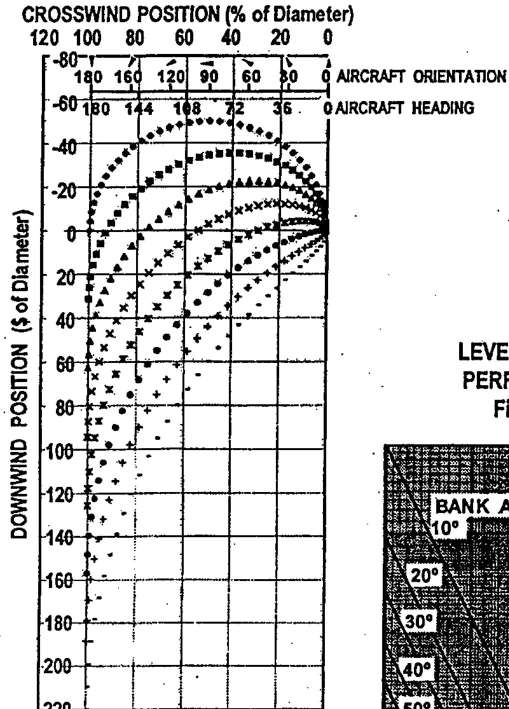


Figure 6B
CONSTANT START POSITION
LEFT TURN DOWNWIND

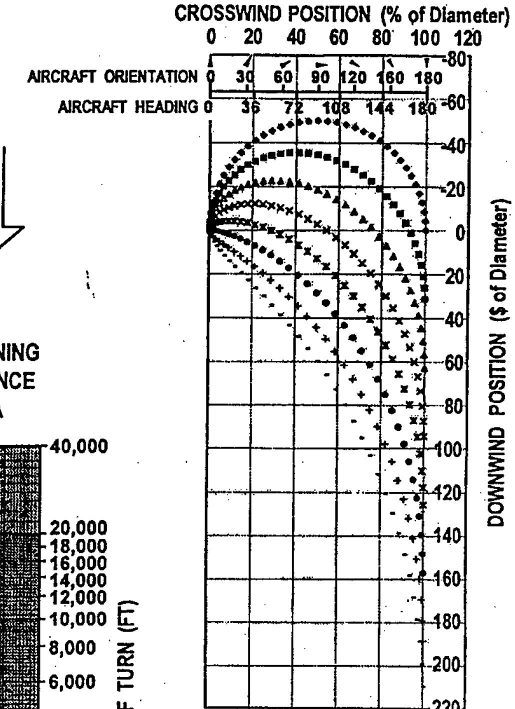
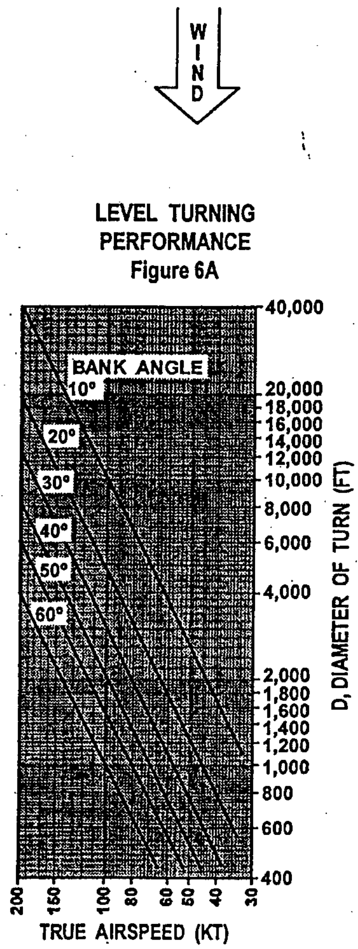


Figure 6C
CONSTANT START POSITION
RIGHT TURN DOWNWIND

LEVEL TURNING PERFORMANCE
Figure 6A



- ◆ K = 0%
- ■ K = 20%
- ▲ K = 40%
- × K = 60%
- ✕ K = 80%
- ● K = 100%
- + K = 120%
- \- K = 140%

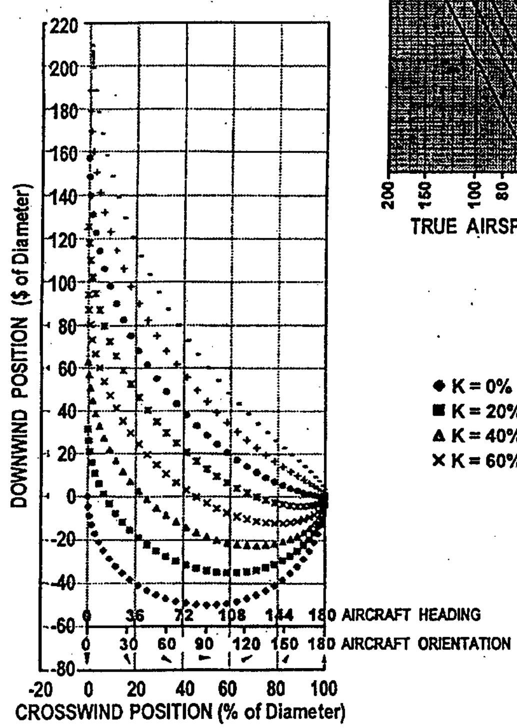


Figure 6D
CONSTANT END POSITION
LEFT TURN UPWIND

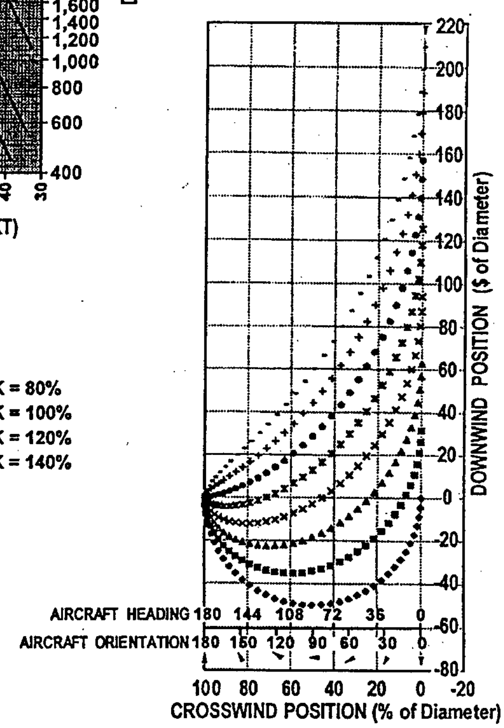


Figure 6E
CONSTANT END POSITION
RIGHT TURN UPWIND

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